Results from the Exoplanet Search Programmes with BEST and TEST

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Abstract. Thüringer Landessternwarte Tautenburg (TLS) has started to operate a small dedicated telescope - the Tautenburg Exoplanet Search Telescope (TEST) - searching for transits of extrasolar planets in photometric time series observations. In a joint effort with the Berlin Exoplanet Search Telescope (BEST) operated by the Institut für Planetenforschung of the "Deutsches Zentrum für Luft- und Raumfahrt (DLR)" at the Observatoire de Haute-Provence (OHP), France, two observing sites are used to optimise transit search. Here, we give a short overview of these systems and the data analysis. We describe a software pipeline that we have set up to identify transit events of extrasolar planets and variable stars in time series data from these and other telescopes, and report on some first results.

1. Introduction

With the discovery of a planet orbiting the star 51 Peg (Mayor and Queloz 1995) the field of extrasolar planet research has become one of the "hot topics" in astrophysics. More than 170 such extrasolar planets are known today. They show us that other planetary systems can greatly differ from our own solar system. The vast majority of these planets has been detected with precise radial velocity measurements. These measurements unveil the periodic Doppler shift in the spectral lines of the planet host star, caused by the orbital motion.

More recently, also transits of extrasolar planets across the disk of their host star have been observed. These observations are of particular interest: they allow us to measure the radii and orbital inclinations of the planets, and thus – together with radial velocity measurements – their masses and densities. Therefore, numerous searches for transiting extrasolar planets have been started in recent years, with optics from standard telephoto lenses up to 4-m class telescopes with wide-field mosaic CCD arrays (Horne 2003). While these experiments are mainly geared towards the detection of Jupiter-like gas giants in short period orbits, future space missions – like CoRoT operated by CNES and Kepler by NASA – even aim at the detection of small terrestrial planets.

One should note, however, that high precision radial velocity measurements require a large number of photons. Therefore, such follow-up is only possible

for planets of brighter host stars. This fact becomes very obvious when looking at the currently known transiting planets: most of them were found by the OGLE-III experiment (Udalski et al. 2002), a 1.3-m telescope operated at Las Campanas Observatory by Warsaw University Observatory, Carnegie Institution of Washington and Princeton University. Their stars have typical brightnesses of $V = 14 - 17$. Even with long integrations at the ESO VLT and Keck telescopes the achievable precision for radial velocity measurements is such, that they limit the accuracy with which physical parameters of these transiting planets and their orbits can be determined (Bouchy et al. 2005).

Photometric transit searches with smaller wide-angle optics may therefore have the great advantage of finding transiting planets around brighter stars. For these, then detailed studies of their atmospheres become possible. The detection of Na and H, C, O in the atmosphere and exosphere of HD 209458 (Charbonneau et al. 2001; Vidal-Madjar et al. 2003; Vidal-Madjar et al. 2004) with the Hubble Space Telescope and the measurements of the albedo of HD 209458 and TrES-1 with the Spitzer Space Telescope (Charbonneau et al. 2005; Deming et al. 2005) are examples of what information can be obtained for planets with brighter host stars. Therefore, Thüringer Landessternwarte Tautenburg (TLS) and the Institut für Planetenforschung of the "Deutsches Zentrum für Luft- und Raumfahrt (DLR)" have decided to operate such small $(20 - 30\,\mathrm{cm})$ telescopes to search for planetary transits of bright host stars. In the course of these measurements also a wealth of variable stars are found.

In Sect. 2 we describe the BEST and TEST telescopes. In Sect. 3 we discuss our the analysis pipeline that we have set up at TLS to find transit events and variable stars in photometric time series data. Finally, we show some early results in Sect. 4.

Figure 1.   The Tautenburg Exoplanet Search Telescope TEST in its dome.

2. The BEST and the TEST

From 2001 to 2003 DLR operated the BEST telescope at the Thüringer Landesternwarte in close collaboration with TLS. BEST is a Flatfield Camera of Schmidt-type with 20 cm aperture and 54 cm focal length (Rauer et al. 2004). It was equipped with an APOGEE CCD camera with 2k×2k pixels giving a field of view of 3.1×3.1 deg^2. This telescope has been moved to the Observatoire de Haute Provence (OHP) in 2004, where it is operated from Berlin and used mainly as support facility for the CoRoT space mission. In Tautenburg, a replacement was installed in a newly constructed dome in the course of 2005. This new telescope – the Tautenburg Exoplanet Search Telescope, or TEST – is a larger version of Flatfield camera with 30 cm aperture and 94 cm focal length (see Fig. 1). It is equipped with an APOGEE CCD camera with 4k×4k pixels with a scale of 2.0 arcsec/pixel, giving a field of view of 2.2×2.2 deg^2. Currently, the BEST is operated in white light, while the TEST observes through an R-band filter. Both telescopes may be equipped with filter wheels for complete filter sets in the future. These, however, have to be custom-build, since commercial filter wheel have too small clear apertures, and would vignette a large part of the field.
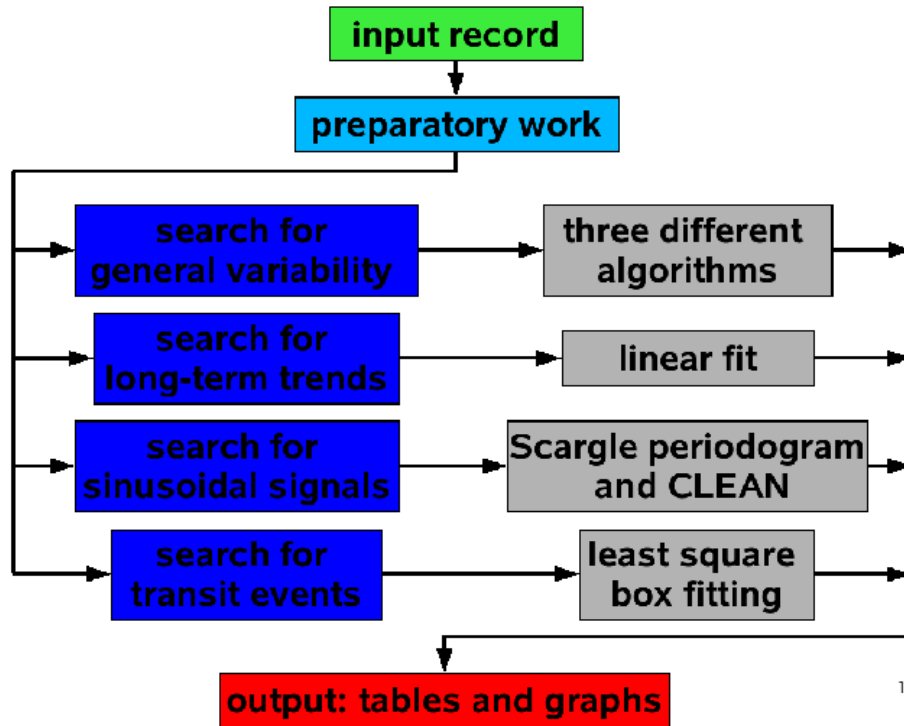

Figure 2.   Schematic of the detection pipeline that we have set up at TLS to identify variable objects in photometric time series data sets.

3.   Searching for transiting planets and variable stars

With both telescopes selected fields in the vicinity of the Galactic plane with high stellar density are being monitored throughout a whole observing season. Furthermore, we obtained extended photometric time series of fields in young open clusters in the course of a programme to study rotation periods of very low-mass stars and brown dwarfs with various other telescopes (Scholz and Eislöffel 2004a; Scholz and Eislöffel 2004b; Scholz and Eislöffel 2005), which we now are searching for planetary transits as well. Currently, target fields of the CoRoT satellite mission are being observed with BEST at the OHP (Karoff et al. 2006).

In all the images from these various time series observations are reduced following standard recipes, including bias subtraction, flat-fielding, and fringe correction where necessary. Then, photometry of all sources on these images is carried out. In the beginning, aperture photometry was used for the BEST data (Rauer et al. 2004). This has been upgraded to differential image analysis in the meantime (Karoff et al. 2006). On the images of the cluster fields from the rotation project, on the other hand, PSF (point spread function) photometry was done using daophot (Stetson 1987).

In all cases the data were then detrended on a nightly basis. We describe in detail how this is being done for the cluster fields from the rotation project in Scholz and Eislöffel (2004a, 2004b, 2005) using non-variable stars in the same fields (see Rauer et al. 2004 for the BEST data). Atmospheric effects like extinction from changing airmass and cirrus are effectively corrected with this approach.

We have then set up a data analysis pipeline to search such detrended photometric time series data sets for transits of extrasolar planets and variable stars (Eigmüller 2006). While these routines have been developed using data from the rotation project and the BEST fields, this pipeline should be capable of handling data from other time series observations equally well.

Since we are searching for different kinds of variable signals, a variety of different algorithms have to be used (see Fig. 2). Initially, a general search for photometric variability is carried out. This step employs three different variability indicators: a) the modified Stetson-Welch variability index (Welch and Stetson 1993; Zhang et al. 2003), b) the standard deviation within each lightcurve as a function of the object brightness, c) a comparison of the mean brightness and standard deviation of fractions (halfs, thirds, quarters ...) of the light curve.

For certain types of variability more specialised algorithms may deliver better detection efficiencies, and at the same time permit the determination of parameters of these signals that allow us already a crude classification of the variable objects. Some objects may exhibit variability on such long time scales, that within our observing window only a linear trend can be observed in their light curves. Others may show periodic signals. Pulsating, rotating, and eclipsing systems with periods shorter than the observing window belong to this group. Although many of their light curves are not strictly sinusoidal, algorithms tailored to the detection of such signals manage to identify those objects very well. We implemented the Scargle-Lomb periodogram search (Scargle 1982), followed by the CLEAN algorithm (Roberts et al. 1987) for this purpose. Then, we determine the significance of the found periods.

Signals for which the duration of variability is short compared to the period length, such as Algol systems and transits of extrasolar planets, are usually not found by these algorithms. These events are instead very favourably detected by the box least-square fitting (BLS) algorithm developed by Kovacs et al. (Kovács et al. 2002). The significance of the detected events is then determined using the signal detection efficieny (SDE). In addition, we can subtract long-term trends or sinusoidal signals that were detected in the earlier steps of the analysis from the light curves in order to increase the sensitivity of the BLS search.
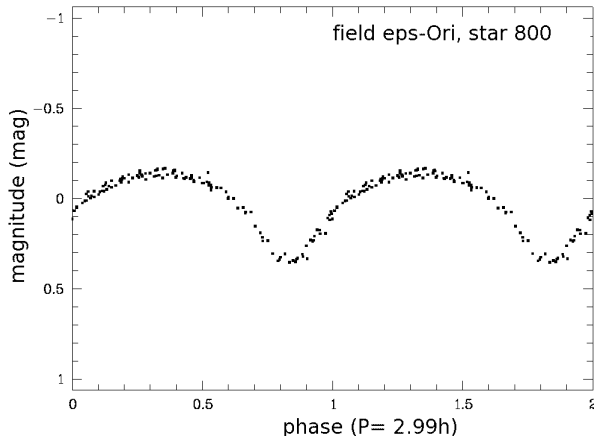

Figure 3.   An eclipsing binary found with the TLS detection pipeline for variable objects in a cluster field near ϵ Orionis.

4.   Early results

We have found many variable objects in the fields from our rotation project and in BEST fields that we searched with our analysis pipeline. In Fig. 3 we show the phased light curve of one of the contact binary systems that we found in one of our time series fields from the rotation project of the young cluster near ϵ Orionis (although this is most likely a background system, not related to this young cluster itself) (Eigmüller 2006).

In the fields that were observed with the BEST while it was operated at TLS, several candidates for transiting extrasolar planets were found. Until now, however, follow-up spectroscopy has identified most of these candidates as eclipsing binary systems. One of these, GSC 3566-1556 (see Fig. 4), was found to be comprised of a G0V-type primary and a M3V-type secondary, causing an eclipse of a depth similar to a planetary transit (Rauer et al. 2004).

The lightcurves obtained with BEST while operated by DLR at TLS will be made available to the community (contact H. Rauer if interested). The data obtained on the CoRoT target fields will be added to the CoRoT ExoData data base.
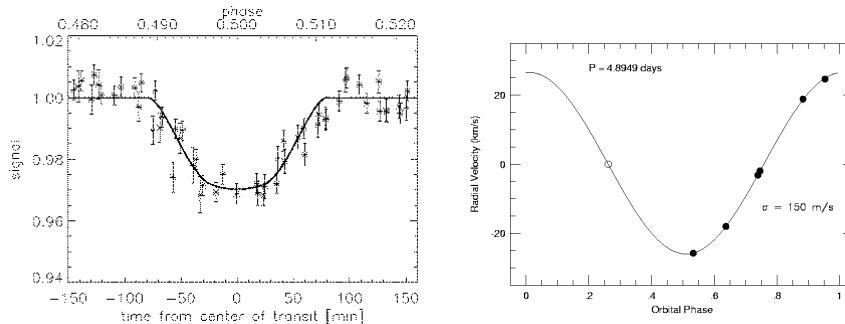
Figure 4.   Left panel: combined light curve of the BEST transit candidate GSC 3566-1556 (Rauer et al. 2004). Right panel: New radial velocity measurements of this candidate obtained with the TLS 2-m telescope. The open circle shows the orbital phase when the transit events were observed.

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